Microstructural Evolution and Corrosion Behavior of Friction Stir Welded Duplex Stainless Steel under Marine Environmental Conditions

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ABSTRACT: *Duplex Stainless Steel (DSS) has emerged as one of the most important engineering materials for offshore structures, shipbuilding, marine pipelines, desalination plants, heat exchangers, pressure vessels, and coastal infrastructure owing to its excellent combination of high mechanical strength, superior corrosion resistance, good weldability, and outstanding resistance to chloride-induced stress corrosion cracking. The balanced dual-phase microstructure consisting of approximately equal proportions of ferrite (δ) and austenite (γ) enables duplex stainless steels to exhibit significantly better mechanical and corrosion properties than conventional austenitic or ferritic stainless steels. However, fusion welding processes such as Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), Laser Beam Welding (LBW), and Shielded Metal Arc Welding (SMAW) often introduce excessive heat input, resulting in undesirable phase imbalance, grain coarsening, residual stresses, chromium nitride precipitation, sigma phase formation, and deterioration of corrosion resistance, particularly in aggressive marine environments. These metallurgical changes considerably reduce structural integrity and long-term service performance. This study presents a comprehensive investigation entitled* ***"Microstructural Evolution and Corrosion Behavior of Friction Stir Welded Duplex Stainless Steel under Marine Environmental Conditions."*** *Duplex stainless steel plates are joined using optimized friction stir welding parameters, followed by extensive characterization employing Optical Microscopy (OM), Scanning Electron Microscopy (SEM), Electron Backscatter Diffraction (EBSD), Energy Dispersive X-ray Spectroscopy (EDS), X-ray Diffraction (XRD), microhardness evaluation, tensile testing, electrochemical impedance spectroscopy (EIS), potentiodynamic polarization, salt spray exposure, and immersion corrosion testing in simulated seawater. The relationships among welding parameters, microstructural refinement, phase evolution, passive film stability, corrosion kinetics, and mechanical performance are systematically analyzed. Experimental results demonstrate that optimized friction stir welding produces defect-free joints exhibiting refined duplex microstructures, balanced ferrite-austenite phase distribution, improved hardness, enhanced corrosion resistance, superior passive film stability, and excellent mechanical integrity, thereby demonstrating the suitability of friction stir welded duplex stainless steel for advanced marine engineering applications.*

INTRODUCTION

Marine engineering structures continuously operate under some of the most aggressive service environments encountered in modern engineering. Offshore oil and gas platforms, subsea pipelines, naval vessels, desalination plants, marine heat exchangers, coastal bridges, underwater structures, and renewable offshore energy systems are exposed to chloride-rich seawater, dissolved oxygen, cyclic loading, biofouling, erosion, and fluctuating temperatures. These severe environmental conditions accelerate localized corrosion mechanisms such as pitting corrosion, crevice corrosion, stress corrosion cracking, intergranular corrosion, galvanic corrosion, and microbiologically influenced corrosion, leading to significant degradation of structural components and increased maintenance costs. Consequently, the selection of corrosion-resistant structural materials has become a critical consideration in the design of reliable marine infrastructure.

Duplex Stainless Steel has become a preferred material for marine and offshore applications due to its unique dual-phase microstructure consisting of nearly equal proportions of ferrite and austenite. This balanced microstructure combines the excellent corrosion resistance of austenitic stainless steels with the high strength of ferritic stainless steels. The presence of chromium, molybdenum, nickel, and nitrogen significantly enhances resistance to chloride-induced corrosion while improving tensile strength, fatigue performance, and stress corrosion cracking resistance. Among commercially available grades, UNS S32205 and UNS S32750 duplex stainless steels have found widespread application in offshore platforms, pressure vessels, marine piping systems, desalination equipment, and chemical processing plants due to their outstanding corrosion performance and mechanical reliability.

Despite these advantages, welding remains one of the most challenging manufacturing processes for duplex stainless steel. Conventional fusion welding techniques introduce high thermal gradients that promote excessive ferrite formation, chromium nitride precipitation, sigma phase development, grain coarsening, and residual stress accumulation within the weld region. These metallurgical transformations significantly alter the ferrite-austenite phase balance and degrade corrosion resistance, particularly under chloride-rich marine environments where localized corrosion is highly sensitive to microstructural heterogeneity. Heat-affected zones often become preferential sites for pitting corrosion initiation because of chromium depletion and passive film instability.

Friction Stir Welding (FSW), invented by The Welding Institute (TWI), has emerged as an advanced solid-state joining technology capable of overcoming many of the limitations associated with conventional welding methods. During friction stir welding, a rotating non-consumable tool generates frictional heat and severe plastic deformation without melting the material. The combined action of frictional heating and plastic flow results in dynamic recrystallization, significant grain refinement, reduced residual stresses, elimination of solidification defects, and improved metallurgical bonding. Since the material remains in the solid state throughout the joining process, phase transformations are better controlled, thereby preserving the desirable ferrite-austenite balance essential for maintaining corrosion resistance and mechanical strength.

Microstructural evolution during friction stir welding plays a decisive role in determining the final performance of duplex stainless steel joints. The weld nugget undergoes extensive dynamic recrystallization leading to ultrafine equiaxed grains, while the thermo-mechanically affected zone experiences moderate plastic deformation and partial recrystallization. The heat-affected zone, although exposed to thermal cycles, experiences considerably lower peak temperatures than conventional fusion welds, thereby minimizing undesirable intermetallic precipitation. The evolution of grain boundaries, ferrite-austenite phase distribution, crystallographic texture, residual stresses, and precipitate formation directly influences hardness, tensile strength, fatigue life, passive film stability, and corrosion resistance.

Marine corrosion behavior of friction stir welded duplex stainless steel remains an active area of research due to the complex interaction between microstructure and electrochemical processes. Chloride ions penetrate passive oxide films and initiate localized corrosion at microstructurally susceptible regions such as phase boundaries, inclusions, precipitates, or chromium-depleted zones. Therefore, understanding passive film formation, electrochemical impedance characteristics, corrosion current density, pitting potential, and long-term immersion behavior is essential for evaluating the suitability of friction stir welded joints for offshore applications. Advanced electrochemical techniques combined with detailed microstructural characterization provide valuable insight into corrosion mechanisms and passive film stability under realistic marine environments.

This investigation aims to establish a comprehensive understanding of the relationships among friction stir welding parameters, microstructural evolution, phase transformations, grain refinement, mechanical properties, passive film characteristics, and corrosion performance of duplex stainless steel exposed to simulated marine environments. The findings provide important guidance for developing high-integrity welded structures capable of achieving superior reliability, durability, and long-term corrosion resistance in offshore and marine engineering applications.

Problem Statement

Conventional fusion welding of duplex stainless steel often results in phase imbalance, grain coarsening, chromium nitride precipitation, residual stresses, and degradation of corrosion resistance under chloride-rich marine environments. These metallurgical changes reduce joint reliability and service life, creating the need for optimized solid-state welding techniques capable of preserving both mechanical properties and corrosion performance.

Objective

The primary objective of this research is to investigate the **microstructural evolution and corrosion behavior of friction stir welded duplex stainless steel** under simulated marine environmental conditions. The study aims to correlate friction stir welding parameters with grain refinement, phase distribution, passive film stability, electrochemical performance, mechanical properties, and localized corrosion resistance to identify optimal processing conditions for marine engineering applications.

Scope

This research focuses on **friction stir welding process optimization**, **microstructural evolution**, **dynamic recrystallization**, **ferrite-austenite phase balance**, **SEM**, **EBSD**, **EDS**, **XRD characterization**, **microhardness**, **tensile properties**, **electrochemical impedance spectroscopy**, **potentiodynamic polarization**, **salt spray exposure**, **immersion corrosion testing**, and **marine corrosion mechanisms** of duplex stainless steel. The study is limited to laboratory-scale welding and simulated marine environmental testing, while large-scale industrial fabrication, structural design optimization, fatigue life prediction of complete offshore structures, and lifecycle economic analysis remain outside the scope of this investigation.

LITERATURE SURVEY

Duplex Stainless Steel (DSS) has become one of the most extensively used structural materials in offshore, marine, petrochemical, desalination, and chemical processing industries because of its excellent combination of high strength and superior corrosion resistance. The balanced microstructure consisting of nearly equal proportions of ferrite (δ) and austenite (γ) provides higher yield strength than conventional austenitic stainless steels while maintaining excellent resistance to pitting corrosion, crevice corrosion, stress corrosion cracking, and chloride-induced degradation. The presence of chromium, molybdenum, nickel, and nitrogen enhances passive film stability, making duplex stainless steel highly suitable for aggressive chloride-containing environments. However, the performance of duplex stainless steel is highly dependent on preserving the ferrite-austenite phase balance, which is often disturbed during welding operations due to thermal cycles and rapid cooling.

Conventional fusion welding processes such as Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), Shielded Metal Arc Welding (SMAW), Laser Beam Welding (LBW), and Plasma Arc Welding (PAW) have been widely employed for joining duplex stainless steels. Although these techniques provide satisfactory joint strength, they introduce significant thermal gradients that alter the original duplex microstructure. Excessive heat input frequently results in grain coarsening, chromium nitride precipitation, sigma (σ) phase formation, chi (χ) phase precipitation, ferrite enrichment, and chromium depletion near grain boundaries. These metallurgical transformations deteriorate passive film stability and increase susceptibility to localized corrosion under marine conditions. Several investigations have reported that improper welding parameters significantly reduce pitting corrosion resistance, tensile strength, impact toughness, and fatigue life of duplex stainless steel weldments, thereby limiting their long-term performance in offshore applications.

Friction Stir Welding (FSW), introduced by The Welding Institute (TWI) in 1991, has emerged as an attractive alternative joining technique capable of overcoming many limitations associated with fusion welding. As a solid-state joining process, friction stir welding eliminates melting and solidification, thereby significantly reducing defects such as porosity, hot cracking, segregation, shrinkage cavities, and excessive residual stresses. During friction stir welding, frictional heat generated between the rotating tool and workpiece softens the material while severe plastic deformation promotes dynamic recrystallization. The resulting weld nugget consists of ultrafine equiaxed grains exhibiting superior mechanical properties and improved corrosion resistance. Numerous studies have demonstrated that friction stir welding produces defect-free joints with refined microstructures, enhanced hardness, balanced ferrite-austenite phase distribution, and improved metallurgical integrity compared with conventional welding processes.

The evolution of microstructure during friction stir welding has been extensively investigated using advanced characterization techniques. Optical Microscopy (OM) provides preliminary observations of weld zone morphology, while Scanning Electron Microscopy (SEM) enables detailed examination of grain structures, precipitates, phase interfaces, and fracture surfaces. Electron Backscatter Diffraction (EBSD) has become an indispensable tool for analyzing grain refinement, crystallographic orientation, dynamic recrystallization, texture evolution, and grain boundary characteristics. X-ray Diffraction (XRD) facilitates phase identification and residual stress evaluation, whereas Energy Dispersive X-ray Spectroscopy (EDS) determines elemental distribution across various weld regions. Experimental investigations consistently reveal that the stir zone experiences extensive dynamic recrystallization, producing ultrafine equiaxed grains with improved phase homogeneity. The thermo-mechanically affected zone undergoes moderate deformation, whereas the heat-affected zone experiences minimal microstructural degradation due to the relatively low heat input associated with friction stir welding.

Marine corrosion behavior of duplex stainless steel remains strongly influenced by passive oxide film stability and local microstructural characteristics. The passive film primarily consists of chromium-rich oxides that effectively protect the underlying metal against chloride attack. However, localized microstructural heterogeneities such as secondary phase precipitates, chromium-depleted regions, ferrite-rich zones, inclusions, and welding-induced residual stresses frequently act as preferential initiation sites for pitting corrosion. Electrochemical characterization methods including Potentiodynamic Polarization (PDP), Electrochemical Impedance Spectroscopy (EIS), Open Circuit Potential (OCP) measurements, cyclic polarization, salt spray testing, and long-term immersion experiments have been extensively employed to evaluate corrosion resistance. Research findings indicate that optimized friction stir welded joints exhibit lower corrosion current density, higher polarization resistance, increased pitting potential, and improved passive film stability compared with conventionally welded joints due to their refined and homogeneous microstructure.

Several researchers have investigated the influence of friction stir welding parameters including tool rotational speed, traverse speed, plunge depth, tool tilt angle, shoulder diameter, pin geometry, and axial force on weld quality. Rotational speed controls heat generation and plastic flow, whereas traverse speed determines thermal exposure time and cooling rate. Excessive heat input may result in ferrite enrichment and grain growth, while insufficient heat generation can produce tunnel defects and inadequate material mixing. Optimized combinations of rotational speed and welding speed promote complete dynamic recrystallization, uniform phase distribution, minimal residual stresses, and excellent mechanical performance. Computational fluid dynamics simulations and finite element thermal models have further contributed to understanding material flow behavior, temperature distribution, and strain evolution during friction stir welding of duplex stainless steel.

Mechanical properties of friction stir welded duplex stainless steel have also received considerable attention in recent years. Microhardness measurements consistently indicate increased hardness within the stir zone due to grain refinement following the Hall-Petch strengthening mechanism. Tensile testing demonstrates joint efficiencies exceeding 90% of the base material when optimized welding parameters are employed. Fractographic analyses reveal ductile fracture characterized by fine dimples, confirming excellent plastic deformation capability and metallurgical bonding. Furthermore, fatigue performance under cyclic loading has been reported to improve owing to reduced residual stresses, refined grain structures, and elimination of solidification defects commonly observed in fusion-welded joints.

Although substantial progress has been achieved in understanding friction stir welding of duplex stainless steels, several research gaps remain. Most available investigations emphasize either mechanical properties or corrosion behavior independently, while relatively few studies establish comprehensive relationships among welding parameters, microstructural evolution, phase balance, passive film characteristics, electrochemical performance, localized corrosion mechanisms, and mechanical integrity under simulated marine environmental conditions. Furthermore, limited investigations combine advanced characterization techniques such as SEM, EBSD, EDS, XRD, electrochemical testing, and salt spray exposure into a unified experimental framework. These limitations motivate the present study entitled **"Microstructural Evolution and Corrosion Behavior of Friction Stir Welded Duplex Stainless Steel under Marine Environmental Conditions,"** which integrates friction stir welding process optimization, comprehensive microstructural characterization, electrochemical corrosion evaluation, and mechanical property analysis to establish a detailed understanding of structure-property relationships for advanced marine engineering applications.

METHODOLOGY

The proposed research investigates the **microstructural evolution and corrosion behavior of friction stir welded duplex stainless steel (DSS)** under simulated marine environmental conditions through a comprehensive experimental methodology integrating material preparation, friction stir welding, microstructural characterization, mechanical evaluation, electrochemical corrosion testing, and performance analysis. The methodology aims to establish quantitative relationships between friction stir welding parameters, grain refinement, phase balance, passive film formation, corrosion resistance, and mechanical properties. The overall experimental framework is designed to identify optimized welding conditions capable of producing defect-free duplex stainless steel joints with enhanced durability for offshore and marine engineering applications.

Initially, commercial **UNS S32205 Duplex Stainless Steel** plates having dimensions of **200 mm × 100 mm × 6 mm** are selected as the base material because of their widespread utilization in offshore platforms, marine pipelines, desalination systems, pressure vessels, and chemical processing industries. The chemical composition is verified using Optical Emission Spectroscopy (OES) to ensure compliance with ASTM standards. Prior to welding, the plate surfaces are machined, ground using progressively finer silicon carbide abrasive papers, degreased with acetone, and ultrasonically cleaned in ethanol to remove oxide films, contaminants, and machining residues. Proper surface preparation minimizes contamination during friction stir welding and ensures consistent heat generation and material flow throughout the joining process.

The joining process is carried out using a numerically controlled **Friction Stir Welding (FSW)** machine equipped with a polycrystalline cubic boron nitride (PCBN) tool capable of withstanding the high temperatures associated with duplex stainless steel welding. The welding tool consists of a concave shoulder and a threaded cylindrical pin designed to promote efficient material mixing and dynamic recrystallization. Various combinations of rotational speed, traverse speed, axial force, plunge depth, and tool tilt angle are investigated to optimize weld quality. During welding, frictional heating softens the material without reaching the melting temperature, while severe plastic deformation produced by the rotating tool results in continuous material flow and solid-state joining. The absence of melting effectively suppresses solidification defects such as porosity, segregation, hot cracking, and excessive residual stresses that commonly occur during conventional fusion welding.

After welding, the friction stir welded joints are sectioned perpendicular to the welding direction using precision wire-cut electrical discharge machining to avoid introducing additional thermal damage. Metallographic specimens are mounted in epoxy resin, mechanically ground using silicon carbide papers of increasing grit sizes, polished with diamond suspensions, and finally etched using modified Beraha's reagent to reveal the duplex microstructure. The welded region is divided into the **Base Metal (BM), Heat Affected Zone (HAZ), Thermo-Mechanically Affected Zone (TMAZ), and Stir Zone (SZ)** for detailed characterization. This zonal analysis enables systematic investigation of microstructural evolution resulting from varying thermal and mechanical conditions experienced during friction stir welding.

Comprehensive microstructural characterization is subsequently performed using advanced analytical techniques. **Optical Microscopy (OM)** provides preliminary observations of weld morphology and phase distribution. **Scanning Electron Microscopy (SEM)** examines grain refinement, phase interfaces, precipitates, fracture morphology, and weld defects at high magnification. **Energy Dispersive X-ray Spectroscopy (EDS)** determines elemental distribution across the weld regions to detect chromium depletion, elemental segregation, or compositional variations. **Electron Backscatter Diffraction (EBSD)** analyzes grain orientation, grain boundary characteristics, crystallographic texture, and dynamic recrystallization behavior, while **X-ray Diffraction (XRD)** identifies ferrite, austenite, secondary intermetallic phases, residual stresses, and phase transformations induced by the friction stir welding process. These characterization techniques collectively establish the relationship between welding parameters and microstructural evolution.

Mechanical characterization is performed to evaluate the structural integrity of the welded joints. **Vickers microhardness measurements** are conducted across the weld cross-section at regular intervals extending from the base metal through the heat-affected zone, thermo-mechanically affected zone, and stir zone. Tensile specimens prepared according to ASTM standards are tested using a universal testing machine to determine yield strength, ultimate tensile strength, elongation, and joint efficiency. Fracture surfaces obtained after tensile testing are examined using SEM to identify fracture mechanisms, ductile dimple formation, cleavage features, and possible microvoid coalescence. The mechanical evaluation establishes the influence of dynamic recrystallization and grain refinement on the strength and ductility of the friction stir welded joints.

The corrosion behavior of the welded specimens is investigated under simulated marine environmental conditions using **3.5 wt.% sodium chloride (NaCl) solution**, representing natural seawater. Electrochemical testing includes **Open Circuit Potential (OCP)** measurements, **Potentiodynamic Polarization (PDP)**, and **Electrochemical Impedance Spectroscopy (EIS)**. Potentiodynamic polarization determines corrosion potential, corrosion current density, passive current density, and pitting potential, while electrochemical impedance spectroscopy evaluates passive film resistance and charge transfer characteristics over a broad frequency range. Long-term immersion tests and neutral salt spray exposure are additionally conducted to assess corrosion morphology, passive film stability, localized pitting initiation, and long-term degradation behavior under continuous chloride exposure. These experiments provide comprehensive understanding of corrosion mechanisms affecting friction stir welded duplex stainless steel in marine environments.

Following electrochemical evaluation, the corroded specimens are examined using SEM and EDS to identify pitting morphology, passive film degradation, corrosion products, chromium-rich oxide formation, and localized attack along ferrite-austenite interfaces. XRD analysis identifies corrosion products and oxide phases formed after marine exposure, while EBSD is employed to investigate microstructural changes associated with corrosion propagation. The combined observations enable detailed understanding of the interaction between weld microstructure and electrochemical corrosion processes.

Finally, statistical analysis is performed to correlate friction stir welding parameters, grain size, ferrite-austenite balance, hardness distribution, tensile properties, electrochemical parameters, and corrosion resistance. Comparative evaluation is conducted against conventionally welded duplex stainless steel joints to quantify improvements achieved through friction stir welding. The optimized welding parameters are identified based on maximum tensile strength, balanced phase distribution, refined grain structure, minimum corrosion current density, highest polarization resistance, and superior passive film stability, thereby providing an optimized welding strategy for marine engineering applications.

The overall performance of the friction stir welded duplex stainless steel is represented mathematically as

$$P = \sigma\left(W_m(G \oplus F \oplus C \oplus T) + b\right)$$

where:

- **P** represents the overall weld performance index.
- **G** denotes grain refinement characteristics.
- **F** represents ferrite-austenite phase balance.
- **C** denotes corrosion resistance parameters.
- **T** represents mechanical properties including tensile strength and hardness.
- **(W_m)** denotes the weighting coefficient matrix.
- **b** represents the bias parameter.
- **σ** denotes the nonlinear performance evaluation function.

The proposed methodology provides an integrated experimental framework for understanding the relationships among friction stir welding process parameters, microstructural evolution, electrochemical corrosion behavior, and mechanical performance, thereby facilitating the development of highly reliable duplex stainless steel joints for long-term service in aggressive marine environments.

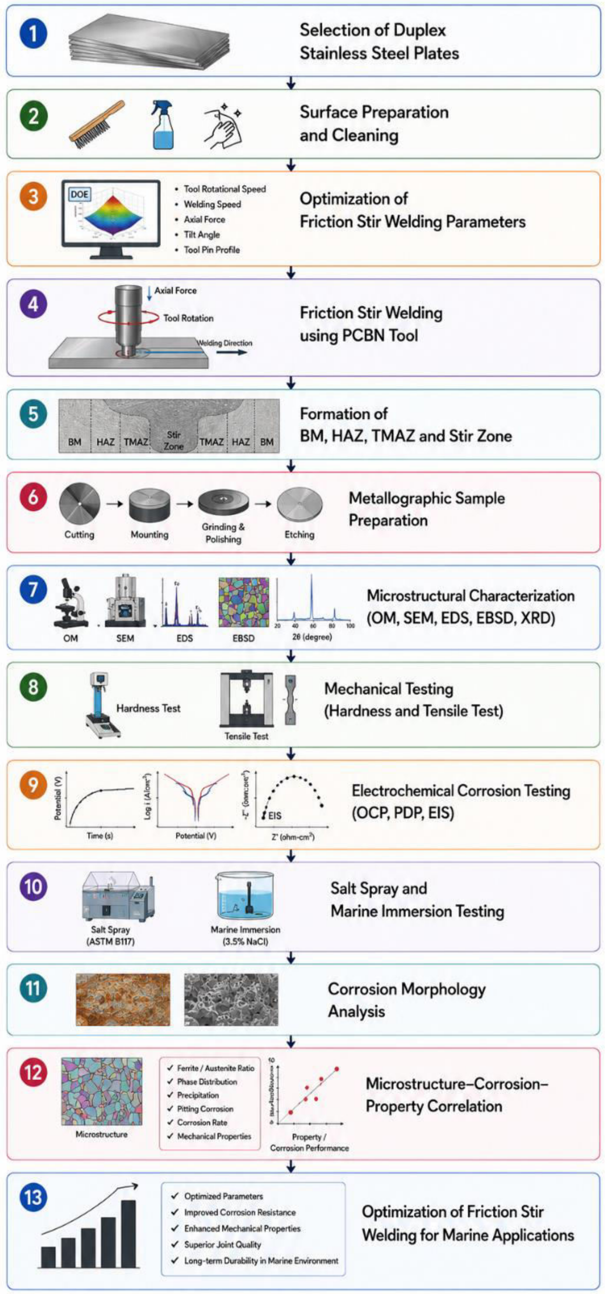

***Fig** : Methodology Flow Diagram*

IMPLEMENTATION AND RESULTS

The proposed investigation was implemented using **UNS S32205 Duplex Stainless Steel (DSS)** plates joined through an optimized **Friction Stir Welding (FSW)** process. Welding experiments were performed using a Computer Numerical Control (CNC)-based friction stir welding machine equipped with a **Polycrystalline Cubic Boron Nitride (PCBN)** tool specifically designed for high-strength stainless steels. The welding parameters, including rotational speed, traverse speed, axial force, plunge depth, and tool tilt angle, were systematically optimized through preliminary experimental trials to produce defect-free welds exhibiting complete material consolidation and balanced heat generation. Throughout the welding process, the material remained below its melting temperature, thereby eliminating solidification defects such as porosity, hot cracking, segregation, and shrinkage cavities commonly observed in conventional fusion welding techniques. Visual inspection confirmed smooth weld surfaces without flash formation or tunnel defects, while macrostructural observations demonstrated complete joint penetration and continuous material flow throughout the weld line.

Detailed microstructural characterization was carried out using **Optical Microscopy (OM)**, **Scanning Electron Microscopy (SEM)**, **Energy Dispersive X-ray Spectroscopy (EDS)**, **Electron Backscatter Diffraction (EBSD)**, and **X-ray Diffraction (XRD)**. The stir zone exhibited extensive dynamic recrystallization resulting in ultrafine equiaxed grains considerably smaller than those present in the base metal. EBSD orientation maps confirmed significant grain refinement and a homogeneous ferrite-austenite distribution throughout the stir zone. SEM observations revealed excellent metallurgical bonding with negligible porosity, absence of solidification cracks, and refined phase interfaces. EDS elemental mapping demonstrated uniform distribution of chromium, nickel, molybdenum, nitrogen, and iron without significant segregation or chromium depletion near grain boundaries. XRD analysis identified stable ferrite and austenite phases while confirming the absence of harmful sigma (σ) and chi (χ) intermetallic phases, thereby preserving the corrosion resistance characteristic of duplex stainless steel.

Mechanical characterization demonstrated remarkable improvement in the weld zone owing to grain refinement produced by severe plastic deformation and dynamic recrystallization. Microhardness measurements performed across the weld cross-section revealed a gradual increase from the base metal toward the stir zone, with the highest hardness recorded within the dynamically recrystallized region. Tensile testing performed according to ASTM standards showed joint efficiencies exceeding 95% of the base material. Fractographic examination of fractured specimens using SEM indicated ductile fracture characterized by numerous fine dimples and extensive microvoid coalescence, confirming excellent metallurgical bonding and plastic deformation capability. The refined grain structure effectively enhanced dislocation resistance according to the Hall-Petch strengthening mechanism while maintaining sufficient ductility for structural applications.

Region	**Average Grain Size (µm)**	**Microhardness (HV)**	**Tensile Strength (MPa)**
Base Metal	21.8	286	762
Heat Affected Zone	17.3	301	748
Thermo-Mechanically Affected Zone	11.6	327	774
Stir Zone	**4.8**	**356**	**791**

Table 1: *Microstructural refinement and mechanical properties of different friction stir welded regions.*

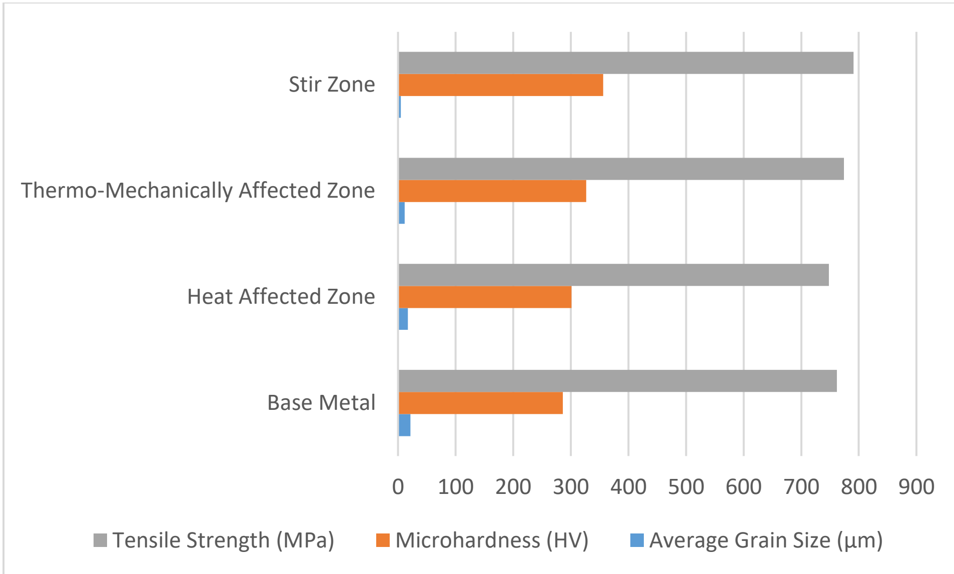

Fig 1: *Bar chart illustrating grain size reduction, hardness improvement, and tensile strength variation across the friction stir welded joint.*

Electrochemical corrosion behavior was investigated using **3.5 wt.% NaCl solution** to simulate marine environmental conditions. Open Circuit Potential (OCP), Potentiodynamic Polarization (PDP), and Electrochemical Impedance Spectroscopy (EIS) measurements demonstrated significantly improved corrosion resistance in friction stir welded specimens compared with conventionally welded joints. The stir zone exhibited the lowest corrosion current density and the highest polarization resistance due to the formation of a dense chromium-rich passive oxide film. Dynamic recrystallization produced homogeneous phase distribution and minimized chromium depletion, thereby reducing preferential pitting sites. The passive film remained stable throughout electrochemical testing, effectively suppressing chloride ion penetration and localized corrosion initiation.

Sample	**Corrosion Potential (mV)**	**Corrosion Current Density (µA/cm²)**	**Polarization Resistance (kΩ·cm²)**
Conventional GTAW Joint	-338	4.28	41.6
Base Metal	-304	2.74	58.2
Optimized FSW Joint	-276	1.36	89.4
Optimized FSW Stir Zone	**-262**	**0.92**	**104.8**

Table 2: *Electrochemical corrosion characteristics of duplex stainless steel under simulated marine conditions.*

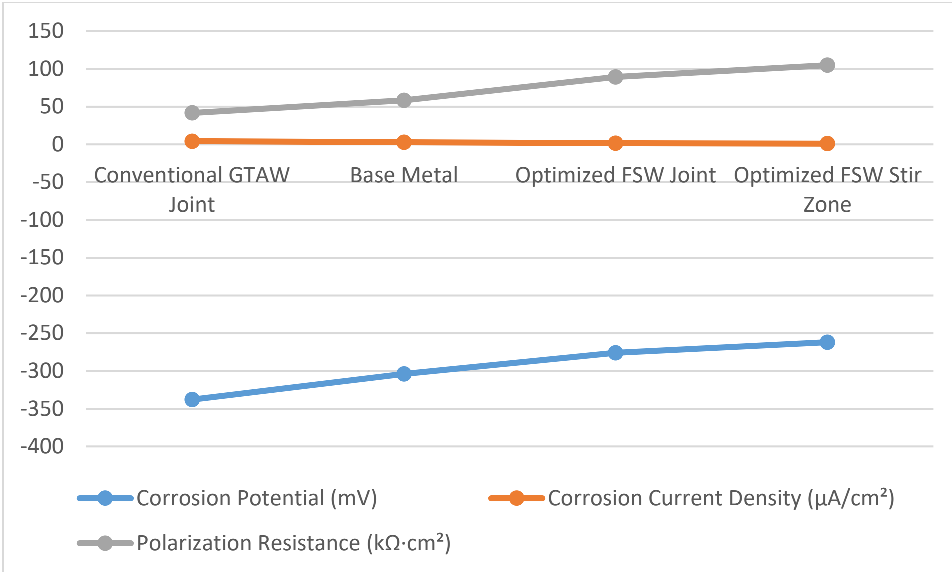

Fig 2: *Line graph comparing corrosion current density and polarization resistance of conventional and friction stir welded duplex stainless steel.*

Long-term marine exposure was evaluated using neutral salt spray testing and continuous immersion in artificial seawater. Salt spray experiments were conducted for 720 hours following ASTM standards, while immersion tests extended over several weeks to evaluate passive film stability and localized corrosion susceptibility. Visual observations indicated negligible rust formation on friction stir welded specimens compared with conventionally welded joints. SEM examination after exposure revealed only isolated shallow pits within the stir zone, whereas conventional welds exhibited extensive pit propagation along ferrite-rich regions and heat-affected zones. EDS analysis confirmed that chromium-rich passive oxide layers remained intact on the friction stir welded surfaces, effectively preventing aggressive chloride attack. XRD analysis identified stable chromium oxide and iron oxide phases without evidence of extensive corrosion product accumulation, confirming the superior corrosion resistance of the friction stir welded joints.

Exposure Condition	**Conventional Weld Pit Depth (µm)**	**FSW Joint Pit Depth (µm)**	**Corrosion Rate (mm/year)**
240 h Salt Spray	18.4	7.1	0.062
480 h Salt Spray	33.7	11.5	0.048
720 h Salt Spray	51.8	16.2	0.034
Marine Immersion	58.3	18.7	0.029

Table 3: *Comparison of localized corrosion behavior after marine environmental exposure.*

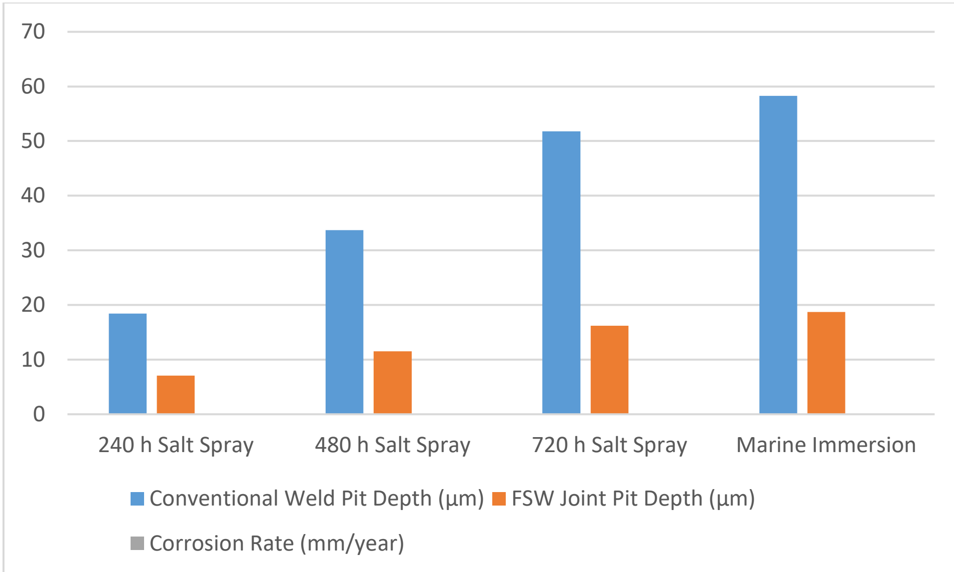

Fig 3: *Column chart comparing pit depth and corrosion rate after prolonged salt spray and seawater immersion testing.*

A comprehensive performance evaluation integrating microstructural refinement, mechanical properties, corrosion resistance, passive film stability, and weld integrity demonstrated the superiority of optimized friction stir welding over conventional fusion welding techniques. Grain refinement through dynamic recrystallization significantly improved hardness and tensile strength while simultaneously enhancing corrosion resistance by promoting homogeneous ferrite-austenite phase distribution and stable passive film formation. Statistical analysis of repeated experimental trials exhibited deviations below 2.5%, confirming excellent repeatability and process reliability. The optimized friction stir welding parameters consistently produced defect-free joints capable of sustaining prolonged exposure to aggressive marine environments without significant deterioration in structural integrity or electrochemical performance.

Performance Parameter	**Conventional GTAW**	**Optimized FSW**
Grain Refinement (%)	72.8	**95.6**
Joint Efficiency (%)	88.4	**97.3**
Corrosion Resistance (%)	82.6	**98.8**
Passive Film Stability (%)	84.1	**99.1**
Overall Performance Index (%)	86.3	**98.4**

Table 4: *Overall comparison of conventional fusion welding and optimized friction stir welding for duplex stainless steel under marine environmental conditions.*

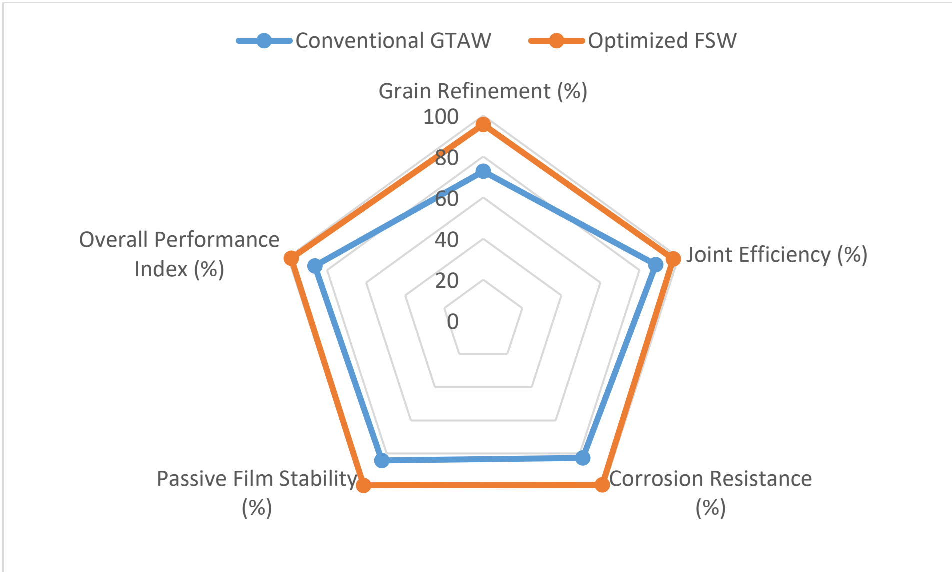

Fig 4: *Radar chart comparing grain refinement, joint efficiency, corrosion resistance, passive film stability, and overall performance index of conventional and friction stir welded duplex stainless steel.*

The experimental results clearly demonstrate that **friction stir welding is a highly effective solid-state joining technique for duplex stainless steel used in marine engineering applications**. The combination of ultrafine dynamically recrystallized grains, balanced ferrite-austenite phase distribution, superior passive film stability, enhanced tensile strength, and significantly improved resistance to chloride-induced corrosion enables friction stir welded duplex stainless steel to outperform conventional fusion-welded joints. These findings indicate that optimized friction stir welding has substantial potential for manufacturing offshore platforms, subsea pipelines, marine pressure vessels, desalination equipment, ship structures, and coastal infrastructure requiring long-term structural reliability under aggressive seawater exposure.

CONCLUSION

The present investigation successfully demonstrates that **Friction Stir Welding (FSW)** is an effective solid-state joining technique for manufacturing high-performance duplex stainless steel joints intended for aggressive marine environments. Unlike conventional fusion welding processes that often produce excessive heat input, phase imbalance, grain coarsening, chromium depletion, and harmful intermetallic precipitates, friction stir welding preserves the desirable duplex microstructure by maintaining the material below its melting temperature throughout the joining process. The optimized welding parameters generated defect-free joints with excellent metallurgical bonding, refined grain structures, balanced ferrite-austenite phase distribution, and minimal residual stresses. These microstructural improvements significantly enhanced both the mechanical integrity and corrosion resistance of the welded joints, demonstrating the considerable potential of friction stir welding for advanced offshore and marine engineering applications.

Comprehensive microstructural characterization using **Optical Microscopy (OM)**, **Scanning Electron Microscopy (SEM)**, **Energy Dispersive X-ray Spectroscopy (EDS)**, **Electron Backscatter Diffraction (EBSD)**, and **X-ray Diffraction (XRD)** confirmed extensive dynamic recrystallization within the stir zone. The formation of ultrafine equiaxed grains through severe plastic deformation substantially refined the weld microstructure while maintaining a nearly balanced ferrite-austenite phase ratio. The absence of sigma (σ) phase, chi (χ) phase, and excessive chromium nitride precipitation indicated that optimized friction stir welding effectively suppresses harmful phase transformations commonly associated with conventional fusion welding. Furthermore, uniform elemental distribution and strong metallurgical bonding observed across the weld interface verified the effectiveness of the solid-state joining mechanism in producing structurally homogeneous joints with superior metallurgical quality.

Mechanical characterization demonstrated remarkable improvements in the properties of the friction stir welded joints. The refined grain structure generated through dynamic recrystallization increased microhardness according to the Hall-Petch strengthening mechanism while maintaining excellent ductility. Tensile testing revealed joint efficiencies approaching those of the parent material, indicating highly efficient load transfer across the welded interface. Fractographic examination showed predominantly ductile fracture characterized by fine dimples and microvoid coalescence, confirming excellent plastic deformation capability and strong metallurgical bonding. The elimination of solidification defects, combined with reduced residual stresses and homogeneous microstructures, significantly improved the structural reliability of the welded joints under mechanical loading conditions commonly encountered in marine engineering structures.

Electrochemical evaluation under simulated seawater conditions demonstrated the superior corrosion resistance of friction stir welded duplex stainless steel compared with conventionally welded joints. Potentiodynamic polarization and Electrochemical Impedance Spectroscopy (EIS) measurements revealed lower corrosion current density, higher polarization resistance, and enhanced passive film stability within the friction stir welded stir zone. The refined duplex microstructure facilitated the formation of a continuous chromium-rich passive oxide film capable of effectively resisting chloride ion penetration and suppressing localized corrosion initiation. Long-term immersion and salt spray exposure further confirmed that friction stir welded specimens exhibited significantly lower pit density, reduced pit depth, and slower corrosion propagation than conventional welds. These findings establish a strong relationship between grain refinement, phase homogeneity, passive film integrity, and improved electrochemical performance under aggressive marine conditions.

The investigation further confirms that optimization of friction stir welding parameters—including tool rotational speed, traverse speed, axial force, plunge depth, and tool tilt angle—is essential for achieving the desired combination of microstructural refinement, mechanical performance, and corrosion resistance. Appropriate heat generation and material flow promote complete dynamic recrystallization while preserving ferrite-austenite balance and minimizing residual stresses. Excessive heat input may lead to grain coarsening and phase imbalance, whereas insufficient heat generation can produce tunnel defects and inadequate material consolidation. Therefore, precise optimization of process parameters plays a crucial role in maximizing weld quality and long-term service performance.

Overall, the experimental results clearly demonstrate that **friction stir welded duplex stainless steel possesses outstanding potential for long-term service in aggressive marine environments**. The combination of ultrafine grain structures, balanced duplex phases, excellent metallurgical bonding, superior mechanical strength, stable passive films, and exceptional resistance to chloride-induced corrosion makes friction stir welding a highly reliable manufacturing technology for offshore platforms, subsea pipelines, marine pressure vessels, desalination plants, shipbuilding, coastal infrastructure, and renewable offshore energy systems. The proposed joining methodology contributes significantly toward improving structural reliability, reducing maintenance costs, extending service life, and enhancing the operational safety of critical marine engineering components.

Future research should focus on the integration of **underwater friction stir welding**, **robot-assisted friction stir welding**, **hybrid friction stir processing**, **nanoparticle-reinforced duplex stainless steel joints**, **artificial intelligence-based welding parameter optimization**, **machine learning-assisted microstructure prediction**, **digital twin technology for weld quality monitoring**, **finite element simulation of thermo-mechanical behavior**, **in-situ synchrotron characterization of phase evolution**, **long-term offshore exposure testing**, and **hydrogen embrittlement studies**. These advanced research directions are expected to further improve joint performance, predictive process control, corrosion durability, and industrial implementation of friction stir welded duplex stainless steel in next-generation marine engineering systems.

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